ANALYSIS OF CLEAR AIR TURBULENCE DURING APRIL 1960

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ABSTRACT

Clear air turbulence (C-A-T) occurrences over the United States reported by pilots in April 1960 are analyzed with reference to weather conditions, wind speed, horizontal and vertical wind shear, thermal stability, and jet stream location and curvature. The day-by-day plot of the occurrences shows that the peak of the C-A-T activity was associated with sharp and well developed troughs which extended far to the south. In the analysis of the data, it is found useful to separate the cases east and west of 103° W. longitude. The cases west of 103° W. indicate greater importance of higher stability and less importance of large horizontal wind shear. The cases east of 103° W., away from the influence of the western mountains, indicate greater importance of decreased stability when combined with either large horizontal or vertical wind shear. Well developed jet streams were apparent with the occurrences in both areas. However, the western cases show a preponderance of cyclonic curvature while the eastern cases show nearly equal division between cyclonic and anticyclonic curvature.

1. INTRODUCTION

The purpose of this study was to make a preliminary analysis of the Clear Air Turbulence (C-A-T) occurrences for April 1960 with reference to the meteorological conditions in order to determine the problems involved in obtaining all the necessary data, in analyzing the data, and in interpreting the results. This study provides some groundwork and guidelines for a broader investigation of C-A-T in addition to furnishing some tentative conclusions regarding the meteorological conditions associated with C-A-T.

Pilot reports for this period collected from the Washington National Airport, United Airlines, and American Airlines, were scanned for clear air turbulence (C-A-T) occurrences. Table 1 is a tabulation of all cases of turbulence over 10,000 feet, except those which definitely were described as in or near thunderstorms, squall lines, or with icing in clouds.

2. METHOD OF ANALYSIS

Since light turbulence is not a major concern to aircraft operations, only the moderate and severe turbulence occurrences were used in the analysis. The following parameters were examined in connection with each occurrence:

a. Surface weather—thunderstorms, squall lines, fronts, showers, clouds.
b. Wind Speed.
c. Horizontal wind shear (in knots per 100 miles).
d. Vertical wind shear (in knots per 1000 feet).
e. Thermal stability (potential temperature lapse rate, ° C. per 1000 feet).
f. Location, intensity, and curvature of the jet stream.

TABLE 1.—*Clear air turbulence occurrences over the United States for April 1960.*

Light	195
Moderate	223
Severe	66
Unknown intensity	6

In this analysis, the parameters were evaluated as near as possible at the actual location and level of the reported turbulence even though greater values of these parameters might be found at some nearby location or level. The actual evaluations were based on the upper-level charts as analyzed at the National Weather Analysis Center (NAWAC) and on all the appropriate rawinsonde, radiosonde, and pilot balloon reports. In most cases, this analysis called for considerable interpolation between observation sites and times. As far as possible, a spacing of 100 miles centered at the site of actual occurrence was used in the evaluation of the horizontal wind shear and a 2000-ft. layer centered at the level of the actual turbulence was used for the evaluation of the vertical wind shear and the stability.

Many of the reports were not specific as to whether the turbulence occurred in clear air or in clouds. The presence of thunderstorms, squall lines, widespread showers and cloud cover as determined by surface maps and other weather data reduced the number of C-A-T cases to approximately 170.

3. SYNOPTIC PATTERNS

The locations of the C-A-T occurrences were plotted on both the maximum wind and 300-mb. charts for the chart time nearest the time of the turbulence. Forty percent of the C-A-T occurrences were between 0600 and 1800 GMT and 60 percent between 1800 and 0600 GMT.

The larger number of occurrences in the latter period is likely due to a greater number of flights during these afternoon and evening hours.

Figure 1 shows the day-by-day occurrences of C-A-T during this period. The four major peaks in the C-A-T activity corresponded to the presence of large-amplitude major troughs aloft in the C-A-T areas during these periods. This is in agreement with the findings of Harrison [1].

This is illustrated in the sequence of 300-mb. charts as analyzed by NAWAC for the April 12–14 period (fig. 2). As the trough deepened and moved eastward, the C-A-T occurrences moved with the trough until it began to dissipate. Similar sequences were apparent during the other peak periods but are not shown in this paper.

4. LOCAL PARAMETERS

The first examination showed a wide scatter in the values of the various local meteorological parameters in connection with the observed C-A-T occurrences. It was not until the occurrences over the coastal ranges and the Rocky Mountains were separated from the occurrences to the east of the Rockies that some patterns and conclusions could be drawn.

Table 2 shows the range in the values of the wind speed, horizontal and vertical wind shear, stability, and the presence and curvature of the jet stream associated with the C-A-T occurrences. A line at approximately 103° W. was used to separate the cases over the western mountains and those to the east of the mountains.

The scatter in the values of the wind speed and the vertical wind shear is about equally great in the eastern and the western occurrences. Over 70 percent of the occurrences had wind speeds of 50 knots or more and about 45 percent of the occurrences were associated with vertical wind shear of 4 knots per 1000 feet or more. A great

TABLE 2.—*Number of cases of occurrence of values of meteorological parameters associated with the C-A-T occurrences.*

	Wind speed (knots)				Horizontal wind shear (knots per 100 miles)			
	0–49	50–74	75–99	≥100	0–14	15–24	25–34	≥35
East of 103° W	18	28	19	8	18	24	20	12
West of 103° W	27	33	17	11	36	34	15	5

	Vertical wind shear (knots per 1000 feet)					Lapse rate (potential temperature) (°C. per 1000 feet)				
	0–1.0	1.1–2.4	2.5–3.9	4.0–6.9	≥7.0	0–1.0	1.1–2.4	2.5–3.9	4.0–5.9	≥6.0
East of 103° W	13	6	13	13	20	26	12	18	11	3
West of 103° W	21	10	9	21	15	20	11	15	18	12

	Jet stream present		Jet stream curvature		Cold Low present
	Yes	No	Cyclonic	Anti-cyclonic	
East of 103° W	63	10	34	29	3
West of 103° W	76	14	56	20	6

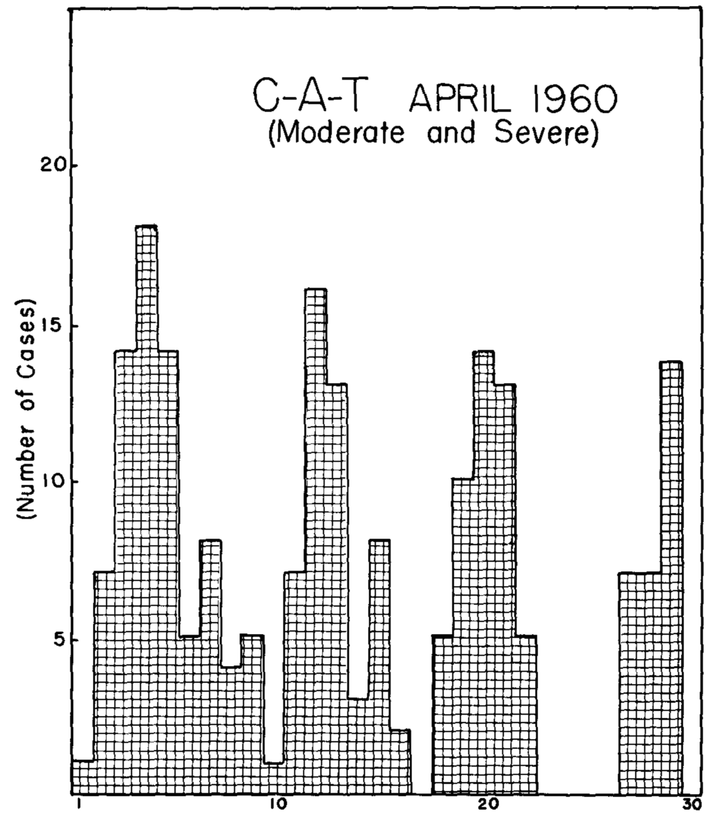

FIGURE 1.—Day-by-day occurrences of clear air turbulence (C-A-T) during April 1960.

preponderance of the occurrences were associated with a pronounced jet stream. However, the western cases show a preponderance of cyclonic curvature while the eastern cases show nearly equal division between cyclonic and anticyclonic curvature of the jet stream.

There appears to be a difference between the western and eastern occurrences with regard to the horizontal wind shear and the stability. Over 77 percent of the western occurrences were associated with a horizontal wind shear of less than 25 knots per 100 miles while only 57 percent of the eastern occurrences were associated with horizontal wind shears of less than 25 knots per 100 miles. Over 46 percent of the western cases had lapse rates of potential temperature ($\Delta\theta/\Delta z$) greater than 4° C. per 1,000 feet as compared to only 20 percent of the eastern occurrences.

Figures 3 and 4 relate the horizontal and vertical wind shear for the C-A-T occurrences in these two areas. The relationship with stability is also indicated through the symbol used for the plotted occurrences. Lines indicating the criteria of 25 knots per 100 miles for horizontal shear and 5 knots per 1,000 feet for vertical shear are drawn on the charts. These criteria are close to the 50 knots per 150 miles given by Harrison [1] and the 6 knots per 1,000 feet given by George [2].

It is important to note that only 16 percent of the eastern C-A-T occurrences (fig. 3), had both the horizontal and vertical shear in excess of the above two criteria and

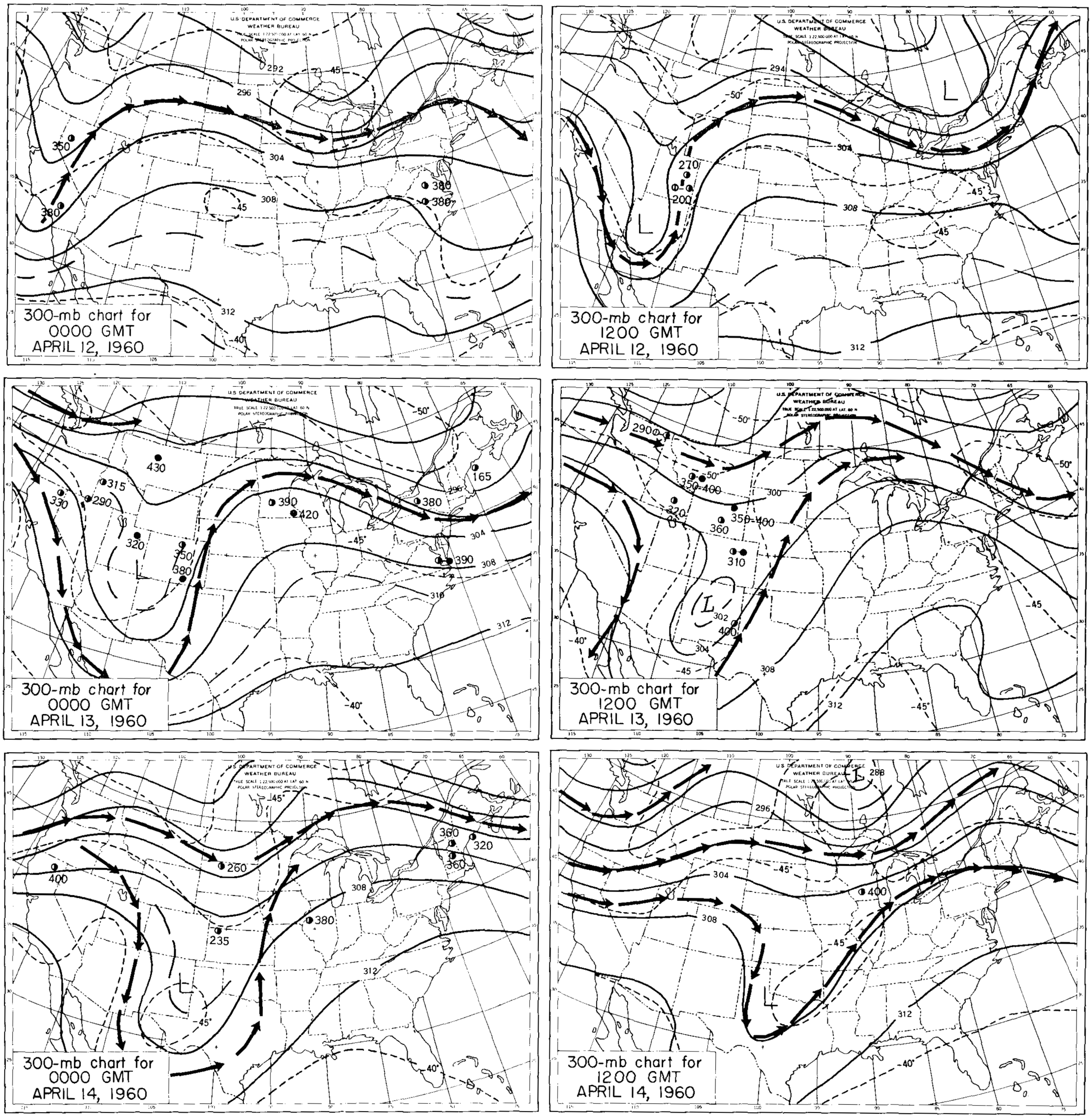

FIGURE 2.—Sequence of 300-mb. charts for the April 12–14, 1960 period of pronounced C-A-T activity. Contours (labeled in hundreds of feet) are given by solid lines, isotherms (°C.) by dashed lines. Jet axis is shown by arrows. Reports of turbulence are plotted as circles (◐ light intensity, ◑ moderate, and ● severe) with height of report in hundreds of feet.

that 33 percent of the cases had both the horizontal and vertical shear below these criteria. However, in 67 percent of the cases, either the horizontal or the vertical wind shear did exceed these criteria. This suggests that it is not necessary to have both a large horizontal wind shear and a large vertical wind shear.

It is interesting to note that where the vertical wind shear was less than 5 knots per 1,000 feet, 53 percent of the eastern C-A-T occurrences had $\Delta\theta/\Delta z$ equal to or less than 1.5° C. per 1,000 feet and only 17 percent had $\Delta\theta/\Delta z$ equal to or greater than 4.5° C. per 1,000 feet. Where the vertical shear was more than 5 knots per 1,000 feet, only

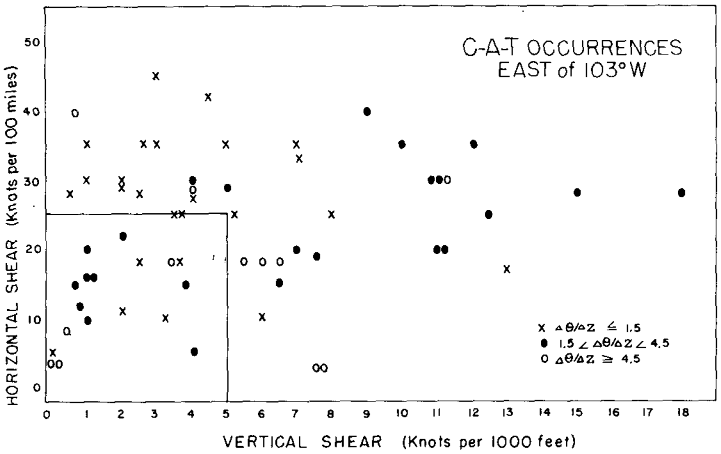

FIGURE 3.—Horizontal and vertical shear for the C-A-T occurrences east of 103° W.

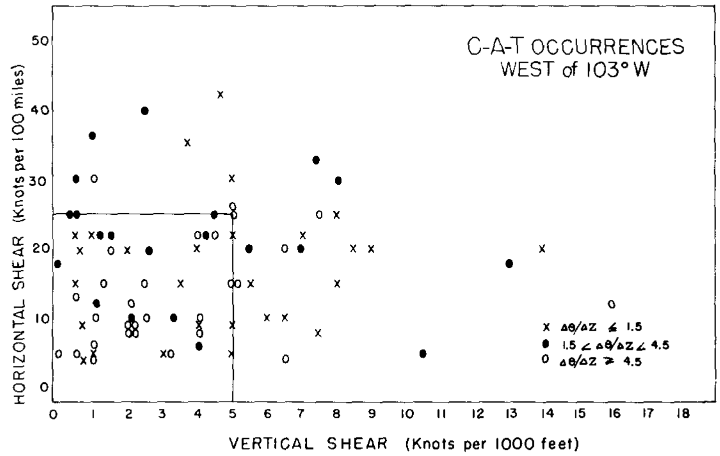

FIGURE 4.—Horizontal and vertical shear for the C-A-T occurrences west of 103° W.

20 percent of the occurrences were associated with the less stable situations. This suggests that lower stability is necessary in the cases where large vertical shear is missing.

Where the horizontal wind shear was equal to or greater than 25 knots per 100 miles, over 58 percent of the eastern C-A-T occurrences were associated with low stability ($\Delta\theta/\Delta z$ equal to or less than 1.5° C. per 1,000 feet) and only 7 percent were associated with high stability ($\Delta\theta/\Delta z$ equal to or greater than 4.5° C. per 1,000 feet). Where the horizontal wind shear was less than 25 knots per 100 miles, the occurrences were associated with a more even distribution of the stability values. Apparently, low stability is more important in the situations with large horizontal wind shear.

Over 62 percent of the western C-A-T occurrences (fig. 4) had both the horizontal wind shear less than 25 knots per 100 miles and the vertical shear less than 5 knots per 1,000 feet. This is in decided contrast to the 33 percent of the eastern cases in this category. This would indicate that strong horizontal and vertical shear are not as important over the mountains as over the eastern area.

Over 33 percent of the western cases were associated with low stability ($\Delta\theta/\Delta z$ equal to or less than 1.5° C. per 1000 feet) and 37 percent with high stability ($\Delta\theta/\Delta z$ equal to or greater than 4.5° C. per 1000 feet). This is in contrast to the 48 percent with low stability and 13 percent with high stability in the eastern C-A-T occurrences.

This indication of the greater importance of high stability over the mountains is in agreement with past work on mountain waves [3] which called for a fairly stable layer with little evidence of any pronounced horizontal wind shear.

In the April data, there were nine cases which seemed to be associated with upper level cold Lows. Six of these nine cases were along the west coast. Other C-A-T cases seemed to be related to very cold tropopause situations. These relationships will require further study.

5. CONCLUSIONS

Because of the indefiniteness of many of the original pilot reports and the possibilities of incorrect evaluation of the meteorological parameters at the scene of the turbulence, conclusions cannot be drawn with too much certainty from the analysis of data in this study. However, it is felt that the general indications as stated are valid.

One important fact which must be recognized in such studies is that the distance between the present upper-air stations is much larger than the scale of the observed turbulence. It is unlikely that there will ever be a network of upper-air stations sufficiently dense and with sufficient frequency of observations to insure the determination of the exact value of the parameters in the actual area and at the time of turbulence occurrence.

This leads to the suggestion that large-scale patterns associated with the development of clear air turbulence should be stressed. These patterns can be detected and measured on the standard synoptic weather charts. Considerable attention must then be given to the various possible atmospheric processes which will lead to the development of these local turbulence situations [4, 5].

Over the western mountains, apparently both the low stability situations which favor mixing and turbulent motions and also the more stable wave situations are important. East of the mountains, low stability is an important factor along with either a strong horizontal or a strong vertical wind shear.

Recent work by Clodman, Morgan, and Ball [6] stressed the importance of gravity waves over continental areas. They pointed out that the combined gravity wave-vertical wind shear mechanism is predominant over land areas. The conclusions in this study seem to be in fair agreement with their ideas. In spite of the much larger area east of 103° W., there were 90 C-A-T cases to the west and 74 cases to the east of the dividing line. The larger number of occurrences over the mountains supports their stress on the influence of the underlying terrain.

Again, there is the handicap of the lack of knowledge about what is taking place in the areas other than those reporting turbulence. A more intensive observation program is needed in which reports of all the non-occurrences of C-A-T as well as the occurrences are available for analysis.

In the meantime, the Weather Bureau is collecting weekly a summary of pilot reports covering C-A-T occurrences from all of the Airway Forecast Centers as well as various airlines. Further papers covering these studies will be forthcoming.

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REFERENCES

1. H. T. Harrison, "The Use of Horizontal Wind Shear in Forecasting High Level Clear Air Turbulence," United Air Lines, Inc., *Meteorology Circular* No. 49, Denver, July 15, 1959.
2. J. J. George, *A Method for the Prediction of Clear Air Turbulence*, Eastern Air Lines, August 1960.
3. DeVer Colson, "Meteorological Problems in Forecasting Mountain Waves," *Bulletin of the American Meteorological Society*, vol. 35, No. 8, Oct. 1954, pp. 363–371.
4. M. E. Balzer and H. T. Harrison, "The Nature of High Level Clear Air Turbulence," United Air Lines, Inc. *Meteorology Circular* No. 48, Denver, July 1, 1959.
5. E. L. Keitz, "Differential Advection as a Factor in Clear-Air Turbulence," *Journal of Meteorology*, vol. 16, No. 1, Feb. 1959, pp. 57–62.
6. J. Clodman, G. M. Morgan Jr., J. T. Ball, *High Level Turbulence*, Research Division, College of Engineering, New York University, Contract No. AF 19(604)–5208, September 1960.

Recent Articles in Other Weather Bureau Periodicals

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